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EFFECTS OF NON-RANDOMNESS ON LINE TRANSECT ESTIMATES OF DOLPHIN SCHOOL ABUNDANCE

by

Elizabeth F. Edwards and Pierre M. Kleiber

ADMINISTRATIVE REPORT LJ-88-25

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EFFECTS OF NON-RANDOMNESS ON LINE TRANSECT ESTIMATES OF DOLPHIN SCHOOL ABUNDANCE

by

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ABSTRACT

Results from a relatively simple mathematical model simulating movements of dolphin schools and tuna vessels searching for those schools indicate that estimates of dolphin school abundance, derived from line transect analysis of sightings data collected by observers on the tuna vessels, can be seriously biased by 1) relatively small-scale non-random searching by vessels and clustering of schools and 2) choice of data stratification algorithm. The most severe biases resulted from interactions between relatively close clustering of dolphin schools and a smoothing and interpolation algorithm developed to estimate school abundance in areas receiving little search effort.

If biasing factors in the school-vessel system remained consistent through time, accurate estimates of change in school abundance could be derived despite bias in estimates of absolute abundance. But serious biases arose in these estimates of change if system biases changed even slightly.

Results emphasize the need to understand patterns of dolphin school distribution in smaller scales of space and time than have been studied previously, and to develop smoothing algorithms more robust to the effects of small-scale non-randomness in school distributions.

INTRODUCTION

The U. S. National Marine Fisheries Service (NMFS) sets quotas for dolphin mortality incidental to fishing operations by the purse-seine fleet for yellowfin tuna (Thunnus albacares) in the eastern tropical Pacific Ocean (ETP). The quota levels depend upon whether dolphin populations are thought to be increasing or decreasing in number, relative to their population levels in 1985.

The most effective method currently available for detecting trends in relative abundance is to use a series of population abundance estimates based on subsequent years' sampling. The most effective method currently available for making these estimates is line transect analysis of dolphin school sightings data (e.g., Buckland and Anganuzzi 1988, Holt 1987. Two data sources are available for these line transect estimates of abundance - 1) data by observers collected during research surveys (RVOD: research vessel observer data) and 2) data collected by observers during commercial fishing operations (TVOD: tuna vessel observer data). RVOD have been preferred by NMFS for monitoring relative abundance of dolphins in the ETP because research surveys can be planned so that sightings operations and subsequent data analyses satisfy adequately the assumptions required by line transect analysis (e.g., Smith 1975[1]). But research surveys are very expensive, and are becoming more so.

Observer-days from tuna vessels account for roughly 95% of the annual observer effort in the ETP, while observer-days from research vessels account for only 5%. In addition, TVOD are relatively inexpensive because they are collected in conjunction with a dolphin mortality monitoring program. This monitoring program has been in operation for the past 14 years, will continue into the foreseeable future, and monitors about 30% of trips by purse-seiners (both U. S. and non-U.S. vessels) each year in the ETP[2]. NMFS has been reluctant to use TVOD to monitor the relative abundance of dolphins because of concern that these data violate seriously some of the fundamental assumptions of line transect analysis (e.g., Polachek 1983), are subject to serious but unquantified and possibly inconsistent biases, and are plagued with artifacts arising from the data

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[1]Smith, T. D. 1975. Estimates of sizes of two populations of porpoise (Stenella) in the eastern tropical Pacific Ocean. Southwest Fisheries Admin. Rept. No. LJ-75-67.

[2] IATTC Annual Reports 1980-1988

collection process (e.g., Hammond and Laake 1983, Barlow and Holt 1986[3], Holt and Cologne 1987, Buckland and Anganuzzi 1988).

However problems of this type are common to most commercial fisheries data and analyses derived from them. It is important to determine whether, despite such difficulties, useful estimates can be derived from such data sets. Toward this end, we have developed a relatively simple model simulating the TVOD collection process. Our purpose in developing the model was twofold: 1) to test the effect of suspected biasing factors on line transect estimates of abundance, and 2) to test new methods of abundance estimation, prior to conducting (expensive) field tests. The unique advantages of simulation modeling in this context are that 1) because we are simulating dolphin abundances and vessel movements within the model itself, we have available the "truth" against which to compare our model-generated estimates of abundance and 2) we have the capability of investigating effects on estimates due to combinations of biasing factors not provided by the environment during the years we happen to have been collecting data.

The philosophy behind building a relatively simple model was that biases shown to be troublesome and methods shown to be inadequate in a simple computer model are not likely to be less troublesome in the real world. We have specifically applied the tenets of Occam's Razor in developing this model, making it as simple as possible while still incorporating the major processes and features contributing to the TVOD data collection process. In these initial simulations, we focused only on estimation of dolphin school abundance, leaving questions about abundance of individual dolphins for a later day. We also assumed that data were collected without artifacts, leaving also that problem for a later set of simulations. Both of these omissions are examples of factors that probably have strong effects on analyses of TVOD, but which are at this stage unnecessary refinements to the simulation model. Our philosophy was that such refinements could be added later if no problems are identified during simulations with the early, most simplified versions of the model.

This paper presents the results of initial simulations testing one hypothesis about one of the most fundamental factors suspected to seriously affect line transect estimates of dolphin abundance derived from TVOD. Specifically, we tested the effect on abundance estimates of non-random clustering by dolphin schools. As part of this analysis we tested also the effects of three types of data stratification prior to line transect

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[3]Barlow, J., and R. S. Holt. 1986. Geographic distributions of species proportions for dolphins in the eastern tropical Pacific. Southwest Fisheries Center, NOAA, La Jolla, CA. Admin. Rept. No. LJ-84-27. 44pp.

estimation of school abundance - 1) no stratification, 2) stratification by raw encounter rate per 1° square, and 3) stratification by smoothed encounter rate per 1° square, using the smoothing and interpolation algorithm developed by the Inter-American Tropical Tuna Commission for deriving estimates of dolphin abundance from line transect analysis of TVOD (Buckland and Anganuzzi 1988). We were primarily interested in the third type of stratification, because the properties of the smoothing algorithm are poorly understood. The other two stratifications were conducted to provide a basis for comparison with the smoothing procedure.

THE MODEL

Model Structure

The model (TOPS: Tuna-vessel Observer Program Simulator) simulates the movements of 75 tuna purse-seiners and either 2500 or 1250 dolphin schools within a 1200x1200 square nautical mile area. Figure 1 provides a graphical comparison of the "study area" simulated by the model, to the entire area within which the tuna-dolphin association is exploited by the purse-seine fleet. Twenty-five hundred dolphin schools is the nominal number of schools expected within a 1200x1200nm area of the ETP, based on Holt's (1985a[4], 1985b[5], 1987) estimates of the total number of dolphins, average size of dolphin schools, and species proportions for the ETP, prorated from the entire ETP to an area 1200x1200nm. Simulations were also run with half this number of schools to investigate the ability of abundance estimates derived under different conditions, to reflect changes in actual abundance in the model. Number of vessels is based on reported size of the ETP purse-seine fleet, assuming about 50% of the fleet will be fishing a given area of this size at any one time (IATTC Annual Reports 1983-1987).

All dolphin schools and all vessels are assumed identical (i.e., all schools include only the northern offshore stock of spotted dolphins (Stenella attenuata), all have the same number of animals, and all are equally visible; all vessels are the same size and are equally adept at sighting dolphin schools). Dolphin schools move at speeds varying between 0.5 and 2.4 knots,

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[4]Holt, R. S. 1985a. Estimates of abundance of dolphin stocks taken incidentally in the eastern tropical Pacific yellowfin fishery. Southwest Fisheries Center Admin. Rept. No. LJ-85-16.

[5]Holt, R. S. 1985b. Estimates of population size of dolphins in the eastern tropical Pacific using line transect methods. Southwest Fisheries Center Admin. Rept. No. LJ-85-20.

depending on conditions of the local environment (see below). All vessels move at 15 knots continuously. Speeds are based on reported averages for dolphin schools (Perrin 1979) and vessels (vessel activity records, NMFS data bases). Vessels are assumed to chase and set upon all sighted schools. Vessels which have set on a school are "removed" from the simulation for 5 hours, simulating the average time to chase, set, collect tuna, release dolphins, and get back under way. Sighted schools are removed from the position of sighting and replaced randomly within 0 to 50nm of the sighting, simulating a variable "rest" period of 0 to 24 hours between one set and the next for sighted schools.

Dolphin schools move in response to the local height and gradient of an "environmental topography". The topography is a grid of constantly spaced peaks of good habitat interrupted by valleys of low-quality habitat. Habitat quality varies between a value of 1 at the peaks for optimum habitats (peaks) to 0 for least favorable habitats, between peaks. Topography is generated as a function of sine waves in two-dimensional space. Topography is either stationary or made to move in one direction at 1 knot. Two combinations of peak spacing and peak shape were used for the simulations reported here - 1) a simple topography of 4 equally spaced peaks with relatively gentle slopes (Figure 2a), and 2) a more complex topography of 16 equally spaced peaks with relatively steep slopes (Figure 2b).

These choices for peak number generates spaces between peak tops of 300 and 600 miles. These spacings were chosen based on approximate distances between clusters of dolphin school sightings from research vessel data[6]. Peak steepness was chosen to simulate either slowly changing environmental conditions (gentle slope) versus rapidly changing conditions (steep slope) such as those which pertain at ocean fronts.

The rate at which the topography moved (1 knot) was chosen to simulate movement of major habitat features affecting dolphin school movements. Because direct identification and measurements of such features have yet to be made, the choice of rate was based on reported speeds of major ocean currents in the eastern tropical Pacific and apparent seasonal movements of major concentrations of dolphin schools. Reported current speeds include 1) 0.1 - 0.3 knots for the core of the Pacific north equatorial current, bordering the fishery area on the north (Seckel 1975), 2) 1.2 - 2.4 knots for the equatorial undercurrent, underlying the fishery area (Wyrtki 1966), and 3) 1.2 - 2.4 knots for maximum speed of the Equatorial Counter-current surface waters, encompassing a majority of the fishing area (Wyrtki 1966). School sightings data from research ships

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[6]Holt 1987, unpubl. data, SWC, P.O. Box 271, La Jolla, CA 92038

indicate that major concentrations of dolphin schools may move seasonally between distant areas at approximately 0.3 knots (200nm/month)[7]. Our choice of 1 knot was based on the assumption that the mechanism(s) responsible for aggregating dolphin schools are most probably related to distributions of prey and water mass signatures indicating presence or absence of the prey.

Dolphins in the ETP consume small (10-50 cm) fish and squid (Perrin et al. 1973). This mobile prey base will in turn be responding to movements of it's own prey base of smaller animals. We reasoned that it is unlikely that this food chain is being swept along as rapidly as the maximum current speeds, but, especially on smaller scales, the distributions of prey and predator are probably moving faster than the speeds apparently characteristic of large-scale seasonal movements. We chose 1 knot as a conservative approximation. It is possible that dolphin aggregating mechanisms move, overall, more slowly than 1 knot, but probably not faster. Thus by comparing simulation results from non-moving topographies versus topographies moving at 1 knot, we have tried to bracket the range of responses likely to occur in the real system.

In our model, dolphin schools were made to respond to these topographies by moving more slowly and turning more frequently in areas where conditions are more favorable and are improving (i.e., around the peaks). In less favorable areas, schools move faster and tend to continue moving forward. Speeds range from 0.5 to 2.4 knots, based on average cruising speeds of dolphin schools in the ETP[8]. Randomness is introduced into school movement by calculating a new direction of movement each time step, with the angle between new and old directions chosen from a circular normal distribution modified by local conditions (i.e., peak height and gradient).

Each vessel's movements are controlled by that vessel's history of dolphin school sightings. Sighting a school causes the sighting vessel to turn more frequently, thus causing the vessel to remain longer in the area where the sighting occurred. Vessels which don't see schools tend to continue forward, thus leaving areas where schools are scarce. Randomness is introduced into vessel movement in the same manner as with dolphin movement; by calculating a new direction of movement each time step, with

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[7]Reilly, S. B., ms in prep., SWC P.O. Box 271, La Jolla, CA 92038

[8]Hedgepeth, J. 1985. Database for dolphin tagging operations in the eastern tropical Pacific, 1969-1978, with discussion of 1978 tagging results. Southwest Fisheries Admin. Rept. No. LJ-85-03. 40pp.

the angle between new and old directions chosen from a circular normal distribution. But in this case, the choice of angle is modified by the sighting history of the vessel. Unlike the rules for dolphin schools, the rules for vessel movement include a function that provides each vessel a "memory". Each sighting increments a variable which influences angle choice so that vessels making several successive sightings will tend to stay in an area longer than vessels making only a few sightings. A dynamics "sightings memory" variable is maintained for each vessel. This variable decays constantly toward zero but is incremented each time a school is sighted. When this variable is low (no recent sights) direction chosen tends to remain the same, and the vessel moves rapidly out of the area. When this variable is high (recent sightings) the vessel tends to reverse it's direction each time step, thereby tending to remain in the area.

Generation of Simulated TVOD

Each simulation began with totally random distributions of both vessels and dolphin schools. Non-random spatial distributions of vessels and schools then proceeded to develop as a function of the environmental topography and movement rules for schools and vessels. Simulations continued for 600 time steps of 1 hour/step.

Estimates of school abundance were based only on TVOD collected during the last 200 steps. By this time, the model had in all cases settled into a quasi-steady state (Figure 3). TVOD collected during each of these last 200 steps included for each vessel; vessel number, total number of miles searched during that step, position of the vessel at the end of the step, and whether or not a school was sighted. Only one school can be sighted per vessel per time step.

TVOD were "collected" for all dolphin schools moving within 2 nautical miles of any vessel. Two nautical miles is the effective strip width found commonly with line transect analyses of real TVOD[9]. All vessels were assumed to carry observers. Observers were always on duty collecting data (i.e., were never "off effort"). Vessels searched continuously (i.e., did not stop at "night").

Data Analyses

TVOD were subsequently aggregated into 1° squares prior to abundance estimation. One-degree squares are the smallest geographic subdivision that retains, with real TVOD, sufficient data for line transect analysis (Buckland and Anganuzzi 1988).

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[9] Hall, personal communication, IATTC, Scripps Institution of Oceanography, La Jolla, CA 92037

Four replicate simulations were conducted for each of eight different cases representing two levels for each of three factors. The factors and levels included 1) complexity of the environmental topography (simple, with 4 gently sloping peaks vs. complex, with 16 steeply sloping peaks), 2) topography dynamics (static vs. sliding left at 1 knot) and 3) dolphin school abundance (2500 vs. 1250 schools).

Stratification Schemes

TVOD collected under each of the 8 cases were subjected to three types of stratification - 1) none, 2) raw encounter rate, and 3) smoothed encounter rate.

In the case of no stratification, school abundance was estimated simply as

[1] $$(TE/AS)*(TA)$$

where TE is total number encounters by all vessels during time steps 400-600, AS is total area searched during that time, and TA is total area simulated (1200x1200nm). In this case, all 1° squares were treated as a single group or stratum.

In stratifying by raw encounter rate, encounter rates (schools encountered/nm searched during the last 200 time steps) were calculated for each 1° square. The squares were subsequently ranked in ascending order of encounter rate, and grouped into (n) strata. Strata were demarcated on the basis of including at least (m) schools (encounters) per stratum. Both (n) and (m) were calculated using an algorithm developed by the Inter-American Tropical Tuna Commission for their line transect analyses of dolphin abundance in the ETP (Buckland and Anganuzzi 1988). School abundance was then estimated for each stratum separately. Total school abundance in the entire 1200x1200nm area was then estimated simply as the sum of these estimates per stratum.

In stratifying by smoothed encounter rate, encounter rates in each 1° square were smoothed according to the algorithms developed by Buckland and Anganuzzi (1988). Squares were then ranked and assigned to strata based on these smoothed encounter rates. This smoothing algorithm generally creates strata composed of contiguous areas of squares, arrayed in decreasing order from area of apparent high density to areas of lower density. It is not uncommon, however, for some squares in a given strata to be scattered in areas isolated from the majority for that stratum.

The smoothed encounter rates generated by the algorithm were used only during this stratification step; school abundances were estimated for each stratum using the raw (actual) encounter rate.

Total abundance of dolphin schools was then estimated as the sum of the estimates for each stratum.

Estimates Derived

Two types of estimates were derived from these simulated TVOD - 1) total abundance of dolphin schools in the entire simulated area, and 2) change in school abundance from one sampling period to another, where this change was estimated simply as the ratio of school abundance estimates derived under two different sets of initial conditions in the model. Thus school abundances were estimated first, and change estimates derived subsequently from these abundances. These estimates of change were calculated as a very simple analogy to a trend estimate, extending in this case over only two sampling periods instead of over a series of estimates. Although the change estimate is only a rough approximation to a trend estimate, general conclusions about the effects of non-randomness on this change estimate will be invalid for trend estimates only in one case; if differences between estimates from successive sampling periods were due only to random changes in the environment that fortuitously "averaged out" over the time periods during which data were collected for the trend estimate. We have as yet no basis for assuming that this fortuitous averaging occurs.

Change estimates were derived under two conditions. Under the first condition the estimate was simply the ratio of the abundance estimate when true density was 1250 schools (low density) to the estimate when the true density was 2500 schools (high density); all other conditions in the model remained the same. This simulates the situation of consistent biases.

Under the second condition, the trend estimate was the ratio of one low-density estimate to one high-density estimate, but the ratio was constructed by selecting abundance estimates from cases which differed in factors other than simply dolphin abundance. This simulates the situation of biases being inconsistent from one sampling period to the next. The three ratios selected from the many possibilities were chosen to simulate three reasonable scenarios in the real ETP and to bracket a range from mild to severe inconsistencies.

The first of the three ratios tested was an estimate of abundance change in the simple environment, where in one case the environment was static during the sampling period and in the other the environment was sliding at one knot. The second ratio was an estimate of abundance change from a simple to a complex environment, the environment remaining static in both cases. The third ratio was an estimate of abundance change from a simple and static environment to a complex and sliding environment. These three cases simulate ratio estimates of abundance changes from,

for example, one year to the next, where conditions in the environment have also changed between years.

RESULTS

Development of Non-Random Distributions

Relatively similar dynamics occurred during the 4 replicate runs of each of the 8 cases (Figure 3). In all cases, non-stratified estimates of total school abundance, calculated for each of the 600 time steps, developed progressively positive biases. Early during each simulation, estimates were relatively accurate. But as schools and vessels became progressively non-randomly distributed (Figures 3a-h) estimates deteriorated due to the concentration of search effort by tuna vessels in the areas where dolphin schools were prevalent and concomitant avoidance of areas with few schools.

Although positive bias developed in all cases, the degree and progression of bias was strongly influenced by environmental topography, both configuration and dynamics. Relatively little bias developed in cases where the topography was relatively non-complex (Figures 3a, 3c) or was sliding at 1 knot (Figures 3b, 3d, 3f, 3h). Very large biases developed in the cases where the topography was complex and static (Figures 3e, 3g).

School Abundance Estimates

Non-stratified estimates of total school abundance, calculated from TVOD collected during the last 200 time steps, of course show the positive bias indicated in the time courses shown in Figure 3. The degree of positive bias in unstratified estimates was not constant, but varied with model conditions (Figure 4). Bias was least for the case of a simple, dynamic environment, slightly higher for the complex, dynamic environment, slightly higher again for the simple, static environment, and dramatically higher for the complex, static environment.

Estimates of school abundance based on stratification by raw encounter rate were in all cases relatively accurate, although estimates tended to be negatively biased for the cases of a simple environment (Figure 4).

Estimates based on stratification by smoothed encounter rate also tended to be negatively biased for the cases of a simple environment (Figure 4). The case of a complex, dynamic environment led to a slight positive bias in abundance estimates. But the complex, static environment led to pronounced overestimates of abundance that rivaled results from the unstratified analyses.

Reducing the underlying density of schools by half, from 2500 to 1250 schools, was mirrored by decreases of approximately one half in school abundance estimates (Figure 4). Patterns of over- or under-estimation under various model conditions remained consistent over both densities (e.g., the most severe bias occurred in both cases under conditions of a complex, static environmental topography).

Change Estimates

When change estimates were derived by comparing cases in which only the underlying density of schools was changed (i.e., when biases remained consistent between sampling periods) the estimates based on raw or smoothed encounter rate stratification were very accurate (Figure 5). Estimates based on unstratified data were strongly biased but analyses of real TVOD are never conducted on unstratified data, so this case is useful only as indication of improvement in estimation achieved by stratifying.

Inconsistent biases produced a dramatically different result. Even relatively small changes in underlying model conditions produced moderate to large biases in the change estimates. Also, these biases were neither consistently positive nor consistently negative, even within a single set of comparisons (Figure 5).

DISCUSSION

School Abundance Estimates

No Stratification

Overestimates were derived from nonstratified data in all cases because vessels (and therefore observers) spent more time (expended more effort) in areas where dolphin schools were abundant, and avoided areas where schools were few (Figure 6). Overestimates of average school abundance per 1° square resulted from this pattern of effort because few samples from low density squares contributed to the average. Overestimates of total school abundance then followed directly by extrapolating this over estimate to the entire area.

Overestimation of school abundance was especially pronounced for the case of a complex, static environment because this condition led to very concentrated clumping of schools within a few 1° squares. Vessels concentrated most of their effort in these few very high density squares. Overestimates were less pronounced in the cases of a simple environment because here the areas of higher density were much more diffuse and not so different from areas of low density. Densities built up much more gradually and to a lower maximum so that vessels sampled many more squares with relatively low density than had been the

case for the complex, static environment. The overestimate of abundance was relatively lower for the case of the complex, dynamic environment for essentially the same reason; the characteristics of the environment produced many more squares with relatively low densities. But here the process generating these relatively low density squares was much different than in the simple environment case. In the complex, dynamic environment the peaks were sliding at one knot. Aggregating the data from the last 200 time steps generated a smeared version of the underlying 16-peak array. Integrated over the entire period of data collection, the areas of dolphin concentration appear as bands across the simulated area, rather than individual peaks (Figure 7). The dolphin schools spread themselves out over a larger number of squares than in the static case, producing lower estimates of average density per square.

Stratification by Raw Encounter Rate

Estimates derived from stratification by raw encounter rate were relatively unbiased in all cases because in these simulations we "collected" an unrealistically large number of TVOD with unrealistically complete coverage of the simulated area. Of the 400 1° squares in our 1200x1200nm area, no more than 6 went unsampled during any simulation. As a result, encounter rates in each square reflected very accurately the true school density in each square. Stratifying by these encounter rates, deriving a different estimate of average school density for each stratum, taking the weighted average of these estimates, and then extrapolating this weighted average to the entire area produced relatively accurate estimates of total school abundance.

The slight negative bias in the cases of a simple environment may be due to a curious effect that was not obvious until we made a movie of vessel and school movements generated by TOPS for a simulation of the simple environment case. It appears in this movie that vessels tend to undersample the areas of highest density in the center of the gradual peaks, because the vessels encounter enough schools along the periphery to keep them turning in these areas. Having found enough along the edges of the peaks to keep them busy, vessels tend to remain in these peripheral areas rather than pushing through to the areas of maximum density. Undersampling the highest densities of course will lead to an underestimate of the average density per square and thus to an underestimate of total abundance. It is not known if this is happening in the ETP fishery.

This avoidance of peak centers did not occur with the complex, static environment used in our simulations, apparently because most of the peak area in this topography occurred within only a few squares (Figure 2b).

Stratification by Smoothed and Interpolated Encounter Rate

Given the apparent accuracy of estimates derived under the stratification by raw encounter rate, it would seem irrelevant to proceed to the more complicated and sometimes ineffective stratification by smoothed encounter rates. But real world tuna vessels never sample the ETP as completely as the simulated vessels sampled the TOPS environments. In most years, fewer than half the vessels carry observers, the fleet as a whole samples less than half the entire ETP, and the sampling that is done tends to be concentrated seasonally in variable geographic areas (Buckland and Anganuzzi 1988).

Because for management purposes we cannot assume that squares with no effort contained no dolphins, we are left with the necessity for estimating densities in those unsampled areas. We have to fill in the holes somehow, so some sort of interpolation method must be used.

In most of the TOPS simulations, Buckland and Anganuzzi's (1988) smoothing and interpolation routines worked quite well, with accuracy rivaling that of the raw encounter rate stratification. But the very poor performance of the smoothing algorithm in the case of a complex, static environment is troubling because we have no data from the field to determine whether or not such topographies exist in the ETP. We suspect that they may because the parameters used in the TOPS model were chosen specifically to be reasonably realistic. In particular, the distance between peaks were chosen to bracket the apparent distances between clusters of dolphin schools as indicated by sightings from research vessels[10] and the movement rates by vessels, schools, and topography approximate observed rates.

The severe bias in the complex static case arises due to an interaction between the effective sampling frequency (in this case, 1° squares), the peak topography, and the mechanics of the algorithm. The algorithm works by calculating for each square a smoothed encounter rate that is a weighted average of encounter rates for all squares within a radius of at least 4 squares. Thus the smoothed rate in each square is affected by rates across a diameter of at least 8 1° squares, or a distance of at least 480 nm (8 x 60nm). In the case of the complex, static topography this minimum distance is greater than the distance between peaks (300 nm) and the relatively precipitous peaks tend to encompass only 3 or 4 squares separated by low density areas several squares across. The smoothing algorithm tends to "fill in" these low density areas, elevating apparent encounter rates in the intervening squares and causing squares to be assigned to

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[10]Holt, unpubl. data, ETP cruises 1987, SWC, P.O. Box 271, La Jolla, CA 92038

strata out of proportion to the true densities of dolphin schools in the squares.

It is possible that the relatively precipitous slopes of the peaks in the complex environment are unrealistic, but in fact these slopes extend over at least 2 1° squares (Figure 2b). This is a distance of at least 120nm. Conditions change across ocean fronts in distances much shorter than this, and ocean fronts are demonstrated aggregating mechanisms for many maine biota (e.g., Owen 1981). Of course, such fronts are never static and the smoothing algorithm worked quite well in the complex, dynamic environment, apparently due to the smearing effect discussed previously. But again we have as yet insufficient data to identify the conditions actually pertaining in the real ETP.

The major point is that the simulations imply that clustering characteristics on relatively small scales (10s to 100s of miles) can have serious effects on estimates of abundance derived via the smoothing algorithm; and as yet we know almost nothing about clustering on this scale in the real ETP. The model results indicate strongly that research needs to be focused in the future either on resolving this lack of information or on developing alternative methods that are not as sensitive as the this smoothing algorithm to these small-scale spatial effects.

Change Estimates

The demonstrated problems with estimating school abundance are serious but in real-world analyses could perhaps be ignored, because the next set of dolphin quotas will be determined not on the basis of estimated abundance (i.e., absolute abundance at some point in time) but rather on the basis of changes in abundance (i.e., in terms of changes in abundance over time, Holt et al. 1987). This is an advantage because as long as nothing other than dolphin abundance changes from one sampling period to the next (i.e., biases remain constant), then accurate estimates can be derived of those changes in abundance. Even if some factors of the environment or the data collection process act to produce inaccurate estimates of absolute abundance, as long as these factors produce the same level of inaccuracy during each sampling period, the differences in estimates of abundance from one period to the next or along a series of periods will accurately reflect actual changes in abundance.

However, we know almost as little about whether biases truly remain constant in the ETP as we know about small scale spatial distributions of dolphin schools. It is obvious from Figure 5 that even relatively small changes in bias can lead to considerable inaccuracies in a change estimate and by implication, a trend estimate. The direction of bias can change as well. A change as simple as moving from a static to a slowly

sliding environment produces an overestimate in the ratio estimate of almost 20% (Figure 5; Lo(2,1)S/Hi(2,1)NS, Case C).

The ratio estimate based on a simple static environment during one sampling and a complex static environment during the other period (Figure 5) is of particular interest, because an effect of this type may be the basis for the anomalous and biologically impossible dip in Buckland and Anganuzzi's (1988) estimates of abundance for northern offshore spotted dolphin (Stenella attenuata) during 1983, the year of an exceptionally strong El Niño. Our simulation results in this case lead to a potentially testable hypothesis about a factor that may have significantly affected analyses of real TVOD. Preliminary analyses of apparent differences in distributions of dolphins during El Niño versus non-El Niño years support this hypothesis that changes in spatial distributions led to inconsistent biases and thus to inaccurate trend estimates during these years[11].

CAVEATS

The results from these simulations are useful primarily in a general sense. The quantitative results are specific to the set of parameters chosen for these particular simulations and are not intended to imply anything about the actual abundance or distributions of either vessels or dolphin schools in the real environment of the ETP. For example, the speed with which non-random distributions develop during the simulations, or the densities that develop in various areas during the course of the runs do not necessarily mimic any dynamics of the real system. Choosing different parameters for the functions controlling dolphin responses to the environment, or vessel responses to dolphins, would change both the rates and spatial characteristics of pattern development and thus estimates of abundance derived from them.

SUMMARY

The changes discussed above in model dynamics with changes in model parameters would not change the general results and implications of these results. We would still find that 1) characteristics of dolphin school distributions on small spatial and temporal scales can significantly bias estimates of school abundance derived from sightings data using current line transect methodology, 2) even mild inconsistencies in biases between sampling periods can produce seriously biased estimates of school abundance, 3) this relatively simple simulation environment provides an effective testing ground for analytical methods (e.g., Buckland and Anganuzzi's smoothing algorithm), and 4) this modeling environment can provide insights into analysis of real

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TVOD (e.g., the anomalous dip in Buckland and Anganuzzi's (1988) estimates of dolphin abundance during 1983).

CONCLUSION

We have found this simplified simulation approach to be a useful and effective tool for identifying critical problems and focusing future areas of research that must be addressed if TVOD are to be an effective source for estimates of dolphin abundance or changes in abundance in the eastern tropical Pacific Ocean. These critical problems are the effect of small-scale non-randomness of dolphin schools, and the interactions between these small-scale patterns, sampling frequency and smoothing algorithms, on estimates of school abundance or change in abundance derived from line transect analysis of sightings data. We need to direct research effort toward identifying and characterizing school distributions within these smaller spatial (and temporal) scales, and toward improving the efficacy of existing methods or developing new methods for analyzing TVOD.

ACKNOWLEDGEMENTS

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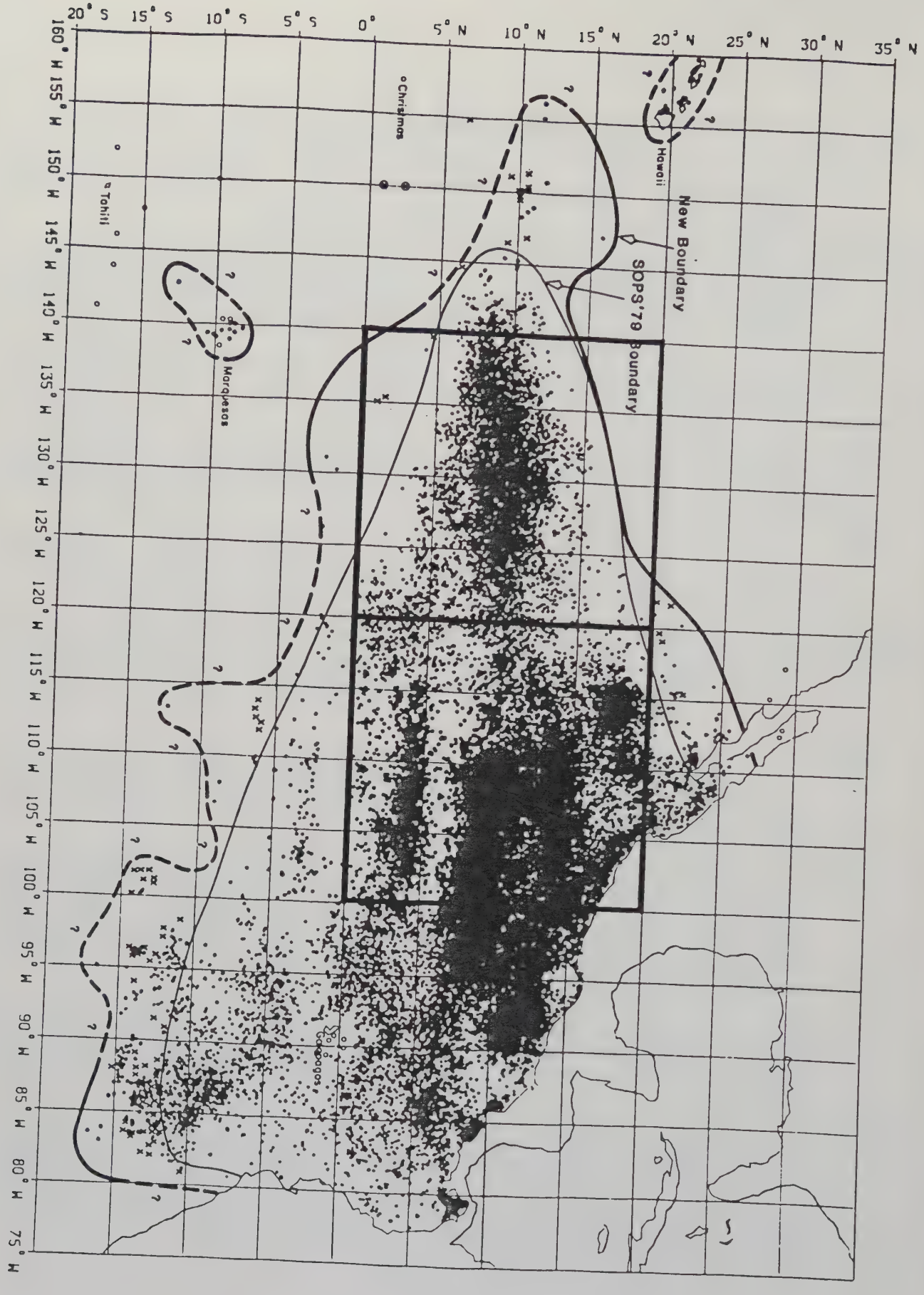
20° S
15° S
10° S
5° S
0°
5° N
10° N
15° N
20° N
25° N
30° N
35° N
160° W
155° W
150° W
145° W
140° W
135° W
130° W
125° W
120° W
115° W
110° W
105° W
100° W
95° W
90° W
85° W
80° W
75° W
Christmas
Tahiti
Marquesas
Hawaii
New Boundary
SDPS'79 Boundary

Figure 1

SIMPLE TOPOGRAPHY
ENVIRON. QUALITY
1.0
0.8
0.6
0.4
0.2
0.1
1200
900
600
300
0
NAUTICAL MILES
0
300
600
900
1200
NAUTICAL MILES

Figure 2a

COMPLEX TOPOGRAPHY
NAUTICAL MILES
0
300
600
900
NAUTICAL MILES
0
300
600
900
1200
ENVIRON. QUALITY
1.0
0.8
0.6
0.4
0.2
0.1

Figure 2b

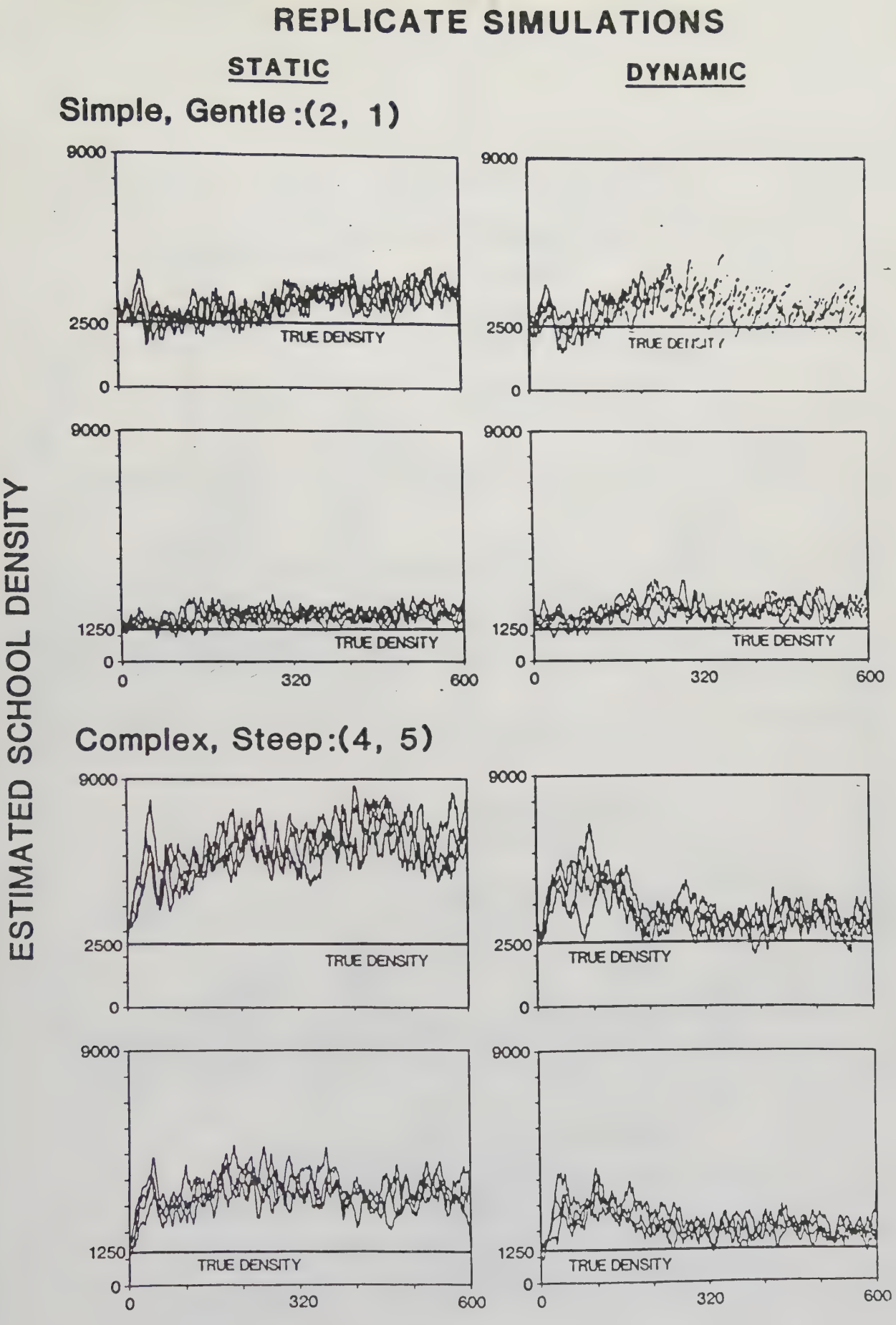
REPLICATE SIMULATIONS
STATIC
DYNAMIC
Simple, Gentle :(2, 1)
9000
2500
0
TRUE DENSITY
1250
320
600
Complex, Steep:(4, 5)
ESTIMATED SCHOOL DENSITY
TIME (hours * 10)

Figure 3

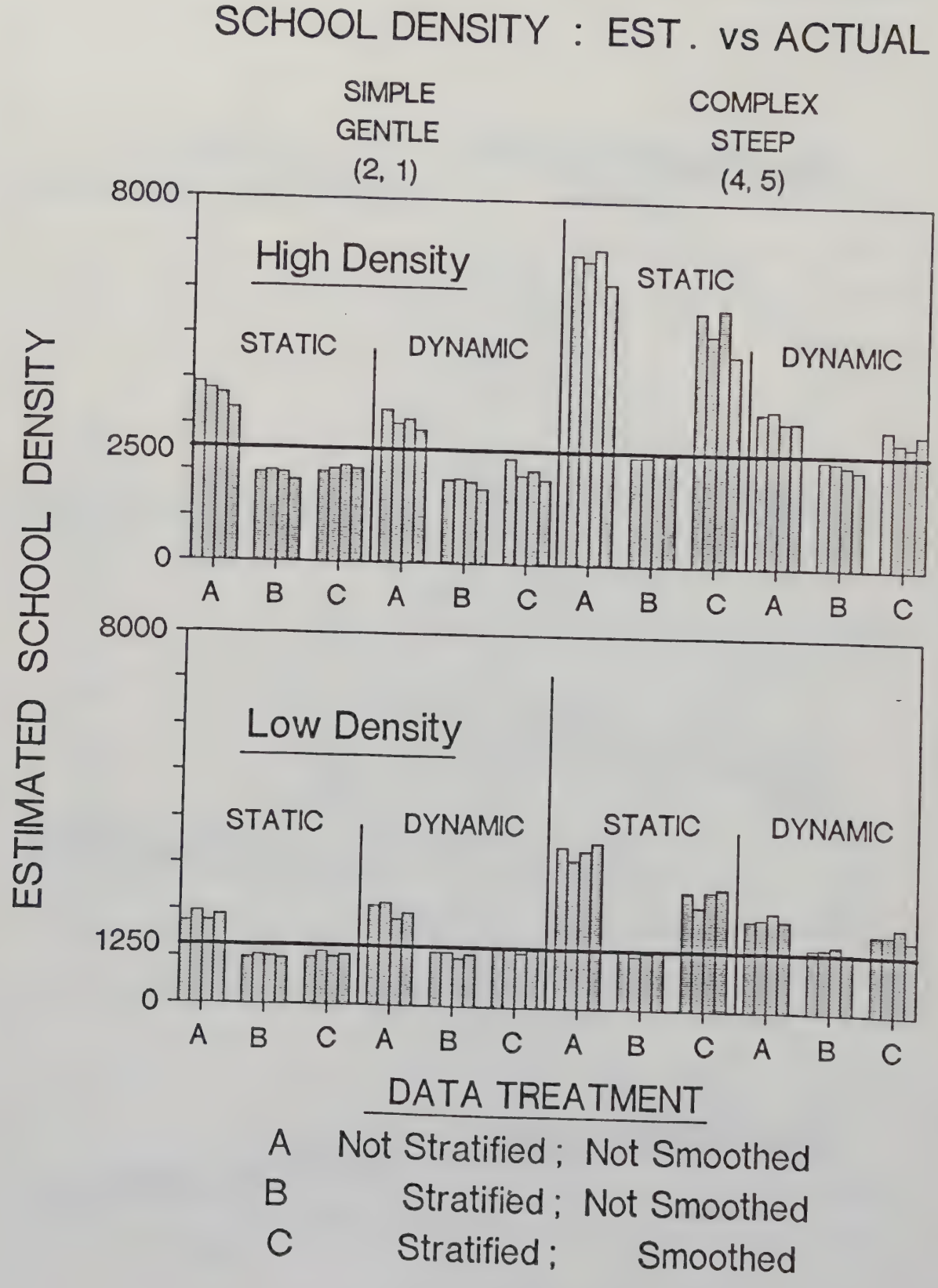
SCHOOL DENSITY : EST. vs ACTUAL
SIMPLE
GENTLE
(2, 1)
COMPLEX
STEEP
(4, 5)
ESTIMATED SCHOOL DENSITY
8000
2500
0
High Density
STATIC
DYNAMIC
STATIC
DYNAMIC
A B C A B C A B C A B C
8000
1250
0
Low Density
STATIC
DYNAMIC
STATIC
DYNAMIC
A B C A B C A B C A B C
DATA TREATMENT
A Not Stratified ; Not Smoothed
B Stratified ; Not Smoothed
C Stratified ; Smoothed

Figure 4

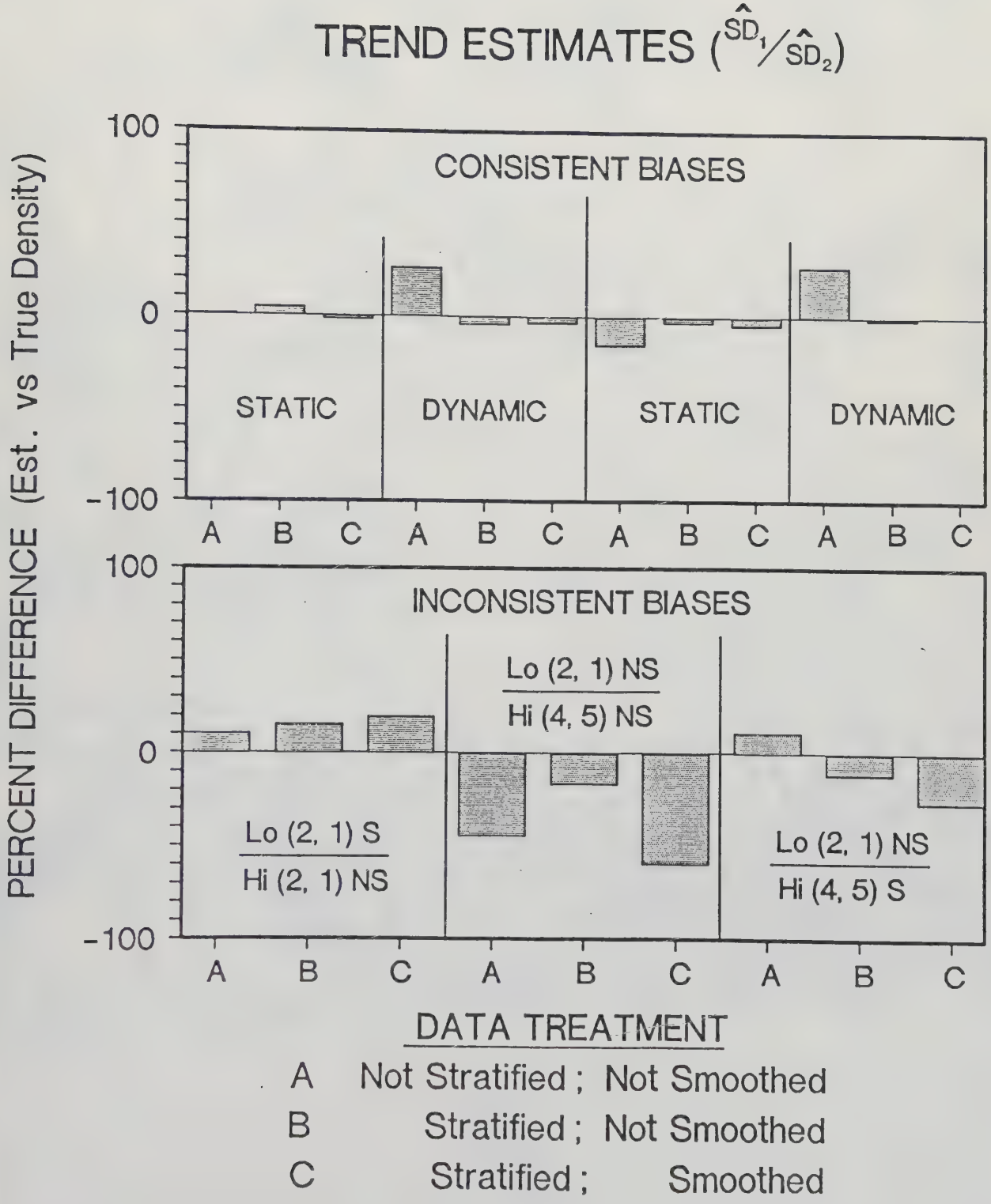
TREND ESTIMATES ($\hat{SD}_1/\hat{SD}_2$)
PERCENT DIFFERENCE (Est. vs True Density)
100
0
-100
CONSISTENT BIASES
STATIC
DYNAMIC
STATIC
DYNAMIC
A B C A B C A B C A B C
INCONSISTENT BIASES
Lo (2, 1) NS
Hi (4, 5) NS
Lo (2, 1) S
Hi (2, 1) NS
Lo (2, 1) NS
Hi (4, 5) S
DATA TREATMENT
A Not Stratified ; Not Smoothed
B Stratified ; Not Smoothed
C Stratified ; Smoothed

Figure 5

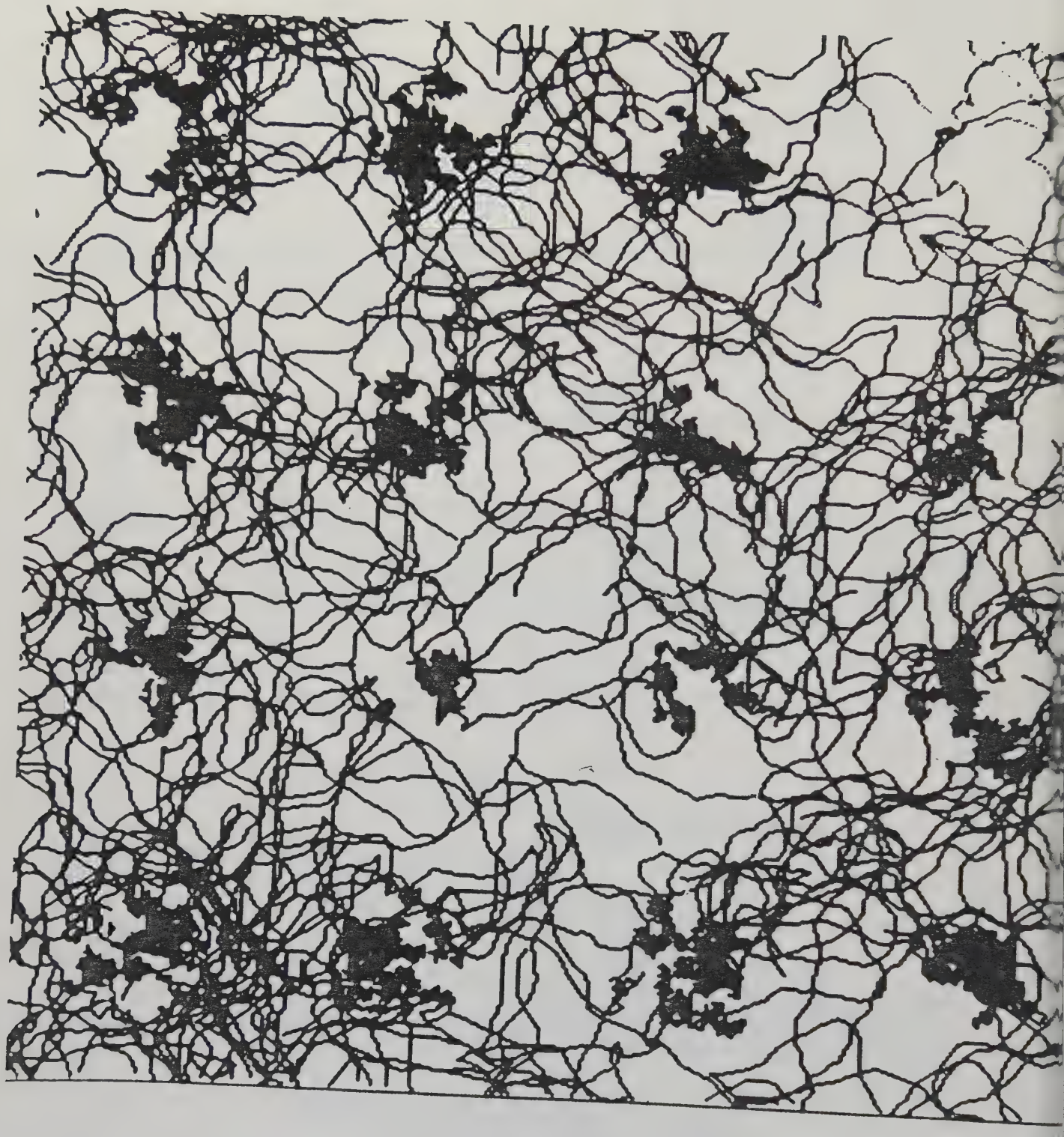

Figure 6

SIMPLE, STATIC
SCHOOL SIGHTINGS
0
100
NAUTICAL MILES
1° square grid
0
300
600
900
NAUTICAL MILES
1° square grid
0
300
600
900
0
100

Figure 7a

SIMPLE, SLIDING
SCHOOL SIGHTINGS
100
0
0
300
600
900
NAUTICAL MILES
1° square grid
0
300
600
900
NAUTICAL MILES
1° square grid

Figure 7b

COMPLEX, STATIC
SCHOOL SIGHTINGS
0
100
NAUTICAL MILES
1° square grid
0
300
600
900
NAUTICAL MILES
1° square grid
0
300
600
900

Figure 7c

COMPLEX, SLIDING
SCHOOL SIGHTINGS
0
100
NAUTICAL MILES
1° square grid
0
300
600
900
NAUTICAL MILES
1° square grid
0
300
600
900

Figure 7d

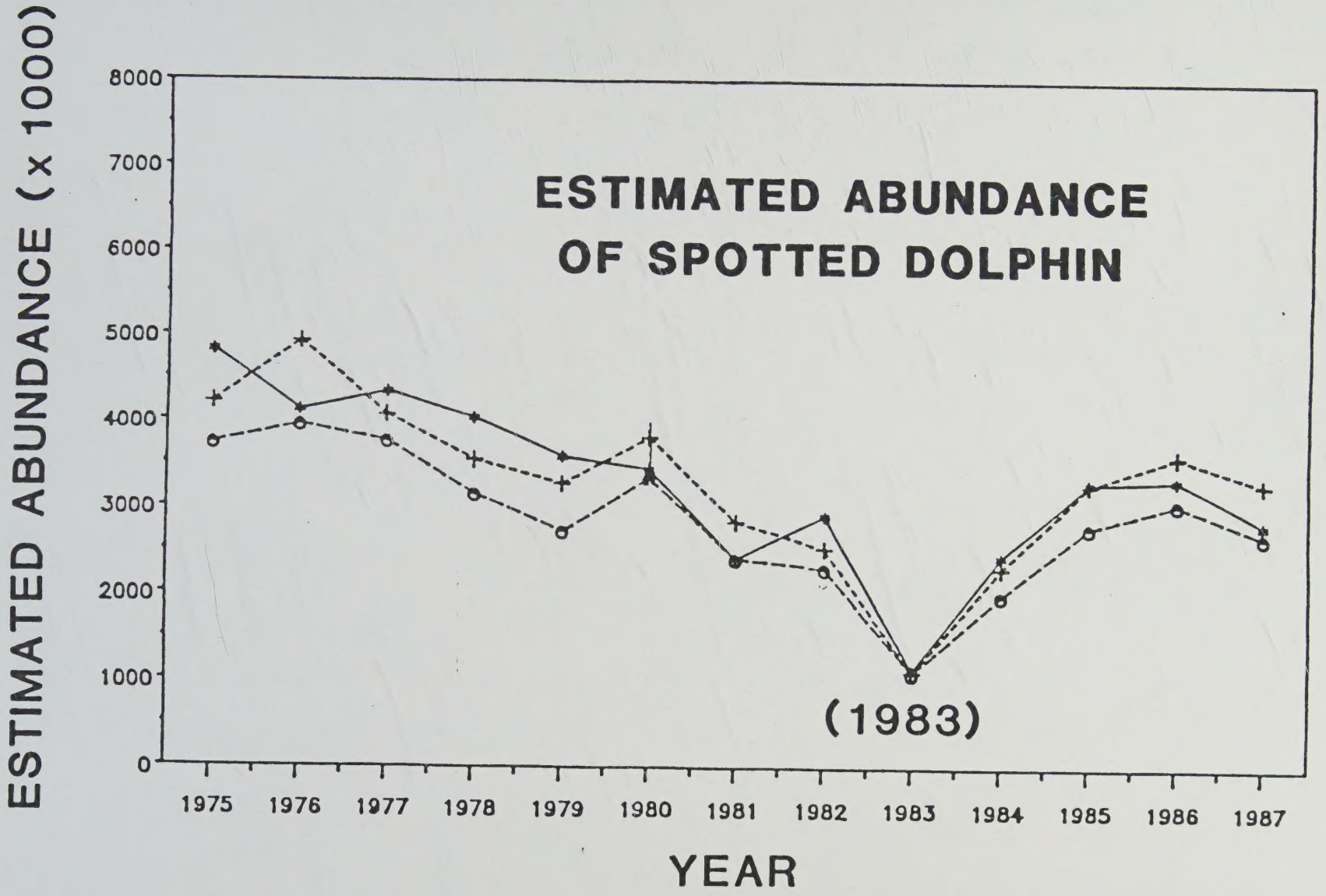
ESTIMATED ABUNDANCE (x 1000)
8000
7000
6000
5000
4000
3000
2000
1000
0
ESTIMATED ABUNDANCE
OF SPOTTED DOLPHIN
(1983)
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
YEAR

Figure 8